FURTHER PETROLOGICAL STUDIES IN GLEN URQUHART, INVERNESS-SHIRE*

III. GRANITIZATION

[Editor's note : Dr. G. H. Francis met his untimely death in a climbing accident in the English Lake District in June 1960. This posthumous paper has been prepared for the press by his former colleague Mr. S. E. Ellis.]

SYNOPSIS

The crystalline rocks north of Milton, Glen Urquhart, consist of a sedimentary series with limestone in the lowest structural position, overlain in turn by kyanite-schist and by psammitic garnet-oligoclase-gneiss, often containing amphibolite lenticles. This group has been folded and metamorphosed, intruded by a mass of serpentinite, and, finally, altered hydrothermally in an episode of alkali metasomatism. The limestone, in its low structural position, is restricted to a number of antiforms making a structural culmination in the unmetasomatized ground. The kyanite-schist and the psammitic gneiss with amphibolite lenticles have now been recognized in outcrops far into the alkali-injected ground. There is no apparent structural boundary between the injected and the uninjected pelitic and psammitic rocks. The difference to be seen in the field is between fresh kyanite-schist and psammitic gneiss on the one side, and the rather uniform feldspathic migmatites derived from both rock types on the other side. For this reason the Geological Survey's separation of the uninjected ground as Lewisian from the injected ground as Moine can no longer be sustained.

INTRODUCTION

The area with which this study is concerned lies on the north side of Glen Urquhart between Polmaily House and Drumnadrochit village, and covers about two square miles. On its north side the glen rises steeply from the alluvial flats of the River Enrick to a rolling plateau at about 800 ft. above sea level. This ground has been over-ridden by ice, and most of the exposures are either *roches moutonnées* or ice-polished pavements. The rocks are coarse-grained and fresh, offering admirable material for petrographic study whilst more than 60 mineral species, common and uncommon, occur within this small area.

(*a*) *Previous Work*

During the nineteenth century the district attracted the attention of several mineral collectors, their work culminating in the thorough mineralogical collection and studies carried out by M. Forster Heddle, and later incorporated in his *Mineralogy of Scotland*. These early accounts have already been noted in greater detail (Francis, 1958).

In the early years of this century the widespread field programme of the Geological Survey reached to the northern fringe of Glen Urquhart in one-inch sheet 83. The

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officers of the Survey continued their mapping and study a short distance further south (that is, into sheet 73) in the area now to be described, because of its unusual interest. The description of the southern part of sheet 83 is given in *The Geology of the Country Round Beauly and Inverness* (Memoir No. 83, 1914) over the initials of E. H. Cunningham Craig. The chief interest of his work in the area lies in his description of folded and metamorphosed sedimentary rocks, together with an intrusion of foliated serpentine rock, which he thought to be separate from, and older than, the widespread feldspathic gneisses of the Moine Assemblage of this area. He characterized this discordance as an inlier of the Lewisian Gneiss Formation within the Moine gneisses of the district.

The present paper is part of a re-examination of the geology of this ground, and follows earlier studies on some of the rock groups found there (Francis, 1955, 1956a, 1958).

(*b*) *Cunningham Craig's Position*

In Memoir No. 83 (pp. 20–23) Cunningham Craig set out the distinctive features of the rocks which he separated from the surrounding Moines on lithological and structural grounds.

> . . . " This mass consists of limestone and gneisses of sedimentary origin into which is intruded a large mass of foliated serpentine. The strike [is] almost at right angles to the general strike of the Moine rocks throughout this district. At the actual junction between these rocks and the Moine schists the two are folded together, but at a short distance the strike of the Moine gneisses begins to swing round and soon resumes the normal north-east and south-west direction." . . .
>
> " The structure in this area of complex gneisses is easily ascertained ; the rocks are folded on axes running approximately north-west, and are usually vertical or very highly inclined. Near the centre of the outcrop, however, the crests of folds and excellent examples of ' pitch ' may be seen. . . . From observations on the pitch of the folding the order of succession of these rocks can be made out ; it is as follows in the present ascending order, though inversion may have taken place before the folding which is now visible :—
>
> 3. Felspathic banded gneisses with basic patches and lenticles.
> 2. Rusty micaceous gneiss with kyanite.
> 1. Limestone.
>
> The lowest rocks appear in the centre and the higher ones toward the sides, from which it is apparent that, disregarding the folding, we are dealing with an anticline rising from under the Moine schists."
>
> " The question at once arises as to the nature of this series of rocks and whether it may be some representative of the Lewisian Gneiss. The evidence so far as it has been disclosed, favours this theory. The underlying series is much more highly crystalline than the surrounding Moine schists ; it strikes north-west and south-east with the normal strike of the Lewisian Gneiss, while in petrological characters the rocks of this group resemble very closely the sedimentary rocks of Glenelg, which are mapped as belonging to the Lewisian

Gneiss. Mr. Clough, who visited the sections in Glen Urquhart, was especially struck by this resemblance in lithological types."[1]

Cunningham Craig then described the lithology of each of the rock types. These descriptions have been quoted, enlarged upon, and to some extent altered in previous papers, mentioned above, and in this paper. Cunningham Craig infers that there is no equivalent in the nearby Moine rocks (mostly feldspathic schists) of the limestone and kyanite-schist found near the serpentinite. The feldspathic banded gneisses, however, are much closer in appearance to the Moine rocks and he described them, and the streaks and bands of hornblende rock that they contain, in some detail. Two important points in his description should here be recalled ; firstly there is a description of granite-like rock :

> " Some of the bands may be classed as muscovite-biotite-gneiss, but the amount of the micas varies greatly, and in some bands there is hardly any. All are markedly felspathic. . . . Some bands south-east of Lochan an Torra Bhuidhe are so completely reconstructed as to resemble a normal granite, the crystallization approaching closely to that of an igneous rock."

Secondly, Cunningham Craig stated his views on the junction between the two formations as follows :—

> . . . " The relation of these felspathic gneisses " [*cf.* Lewisian] " to the Moine schists is a subject of some obscurity. The two are folded together somewhat intimately, and the line between them can often be only approximately fixed, as the marginal beds of the Moine gneisses are somewhat similar in composition and even in crystallization to the Lewisian rocks. In such cases the presence of lenticles of hornblende-schist has been taken as proof that the rock containing them is Lewisian, and the absence of such basic lenticles as indicating that it is probably part of the Moine Series." . . . " Sections in several localities indicate that different beds among these older gneisses come in contact with the marginal beds of the Moines, but beyond this there is no evidence to suggest an unconformability. If the rocks of the Moine series do lie unconformably upon this outcrop of older gneiss the subsequent folding and metamorphism have practically destroyed the evidence by which such a relation could be determined."

Cunningham Craig's position is thus based upon certain lithological and structural differences between the two rock groups. The ground which he identified with the Lewisian contains serpentinite, marble and kyanite-schist, all known from the Foreland and from certain Lewisian Inliers within the Moines (notably that of Glenelg), and all rare amongst Moine rocks, particularly those in the immediate neighbourhood. The (structurally) highest bed, which is a feldspathic gneiss, he found less easy to separate from the surrounding Moine rocks, but he used the criterion that the presence of hornblendic lenticles can be "*taken as proof*" of Lewisian age.[2] On the structural side Cunningham Craig has laid emphasis on the two strike directions : one towards the north-west, the other towards the north-

[1] Clifford (1958) states, on the other hand, that the Glen Urquhart kyanite-schist is *unlike* Lewisian, and *like* Moine kyanite-schists from southern Ross-shire.

[2] The italics are G. H. F's.

east ; the former matching known Lewisian elsewhere, and the latter belonging both to the local and to many other areas of Moine rocks. On the second structural point, unconformity between the formations, his account is so cautious as to sound as if it would not be proffered were it not for the supporting evidence of contrasted lithology.

GEOLOGICAL SETTING

(*a*) *The Position Adopted in this Work*

This re-examination of Cunningham Craig's Lewisian Inlier in Glen Urquhart leads directly to a consideration of the line of unconformity which he mapped. If it is valid it separates (as he maintained) rocks which are different in age and in type. Moreover, obscured, half obscured or apparent, it must be a line of sedimentary discordance. Part of this mapped line of unconformity is published in one-inch sheet 83. The remainder (extending into sheet 73) is not published, but it is discussed in Memoir No. 83, for the Inlier was examined as a whole, disregarding its fortuitous slicing in two by the map grid. It is thus, perhaps, permissible to consider not only the published part of the unconformity but also its extension into sheet 73 (which I have had the privilege of examining in a six-inch MS. map at the Geological Survey Office at Edinburgh). Apart from small mapping errors of the order of a few yards Cunningham Craig's Inlier stands or falls by reference to his line of unconformity. If this line is considerably shifted then there are no real differences between his Lewisian and his Moine rocks in the area between his line and any new line that is drawn ; what was one formation to him really belongs to the other formation, and the structural discordance marked by his line is in the event, merely fanciful. Therefore if his line is found to be unreal the area must either be accepted as all Moine, or another and quite distinct Lewisian Inlier must be proposed upon new evidence of lithological difference and structural discordance (if such exist).

There is one geological feature in the area whose possible significance was not appreciated by Cunningham Craig, although he observed and recorded it. This is the reconstruction of schist " so completely . . . as to resemble a normal granite ". Throughout the district the evidence of alkali injection is writ large upon the rocks. Pegmatites, pegmatitic stringers and quartz veins are everywhere to be found, the schists can be seen to grade over into considerable areas of granite-gneiss, amphibolite alters to coarse biotite skarn, limestone to calc-silicate skarn and serpentinite to amphibole-biotite skarn. Injection effects in serpentinites, and in limestones with their adjacent pelites, have already been discussed (Francis, 1955, 1956a, 1958) ; and in this *Bulletin* the alterations of kyanite-schist and psammitic gneiss by the same injection will be described. The alteration of these rocks by alkali metasomatism is sufficient to make difficult the identification of the altered rock with the unaltered rock in the field, and it is this difficulty alone which apparently has led to the recognition of two rock groups where only one exists. (The " Lewisian " ground and the Moine ground both contain kyanite-schist and both contain psammitic gneiss with hornblendic lenticles.) It is in the ground which Cunningham Craig accepted as Moine that injection reaches its peak ; here the kyanite has been altered completely to white mica and the hornblendic lenticles have in some cases been biotitized and strung out by accompanying movements so as to become inconspicuous. At the same time pink potash feldspar increasingly appears in the injected kyanite-schist and psammitic gneiss on passing toward injection centres. Thus the whole group of changes tends to separate an apparently single formation (the Moine) on the one hand from a formation with two beds containing characteristic minerals (the " Lewisian ") on the other hand. The limestone in the " Lewisian " ground appears only in the cores of antiform culminations, and presumably does not

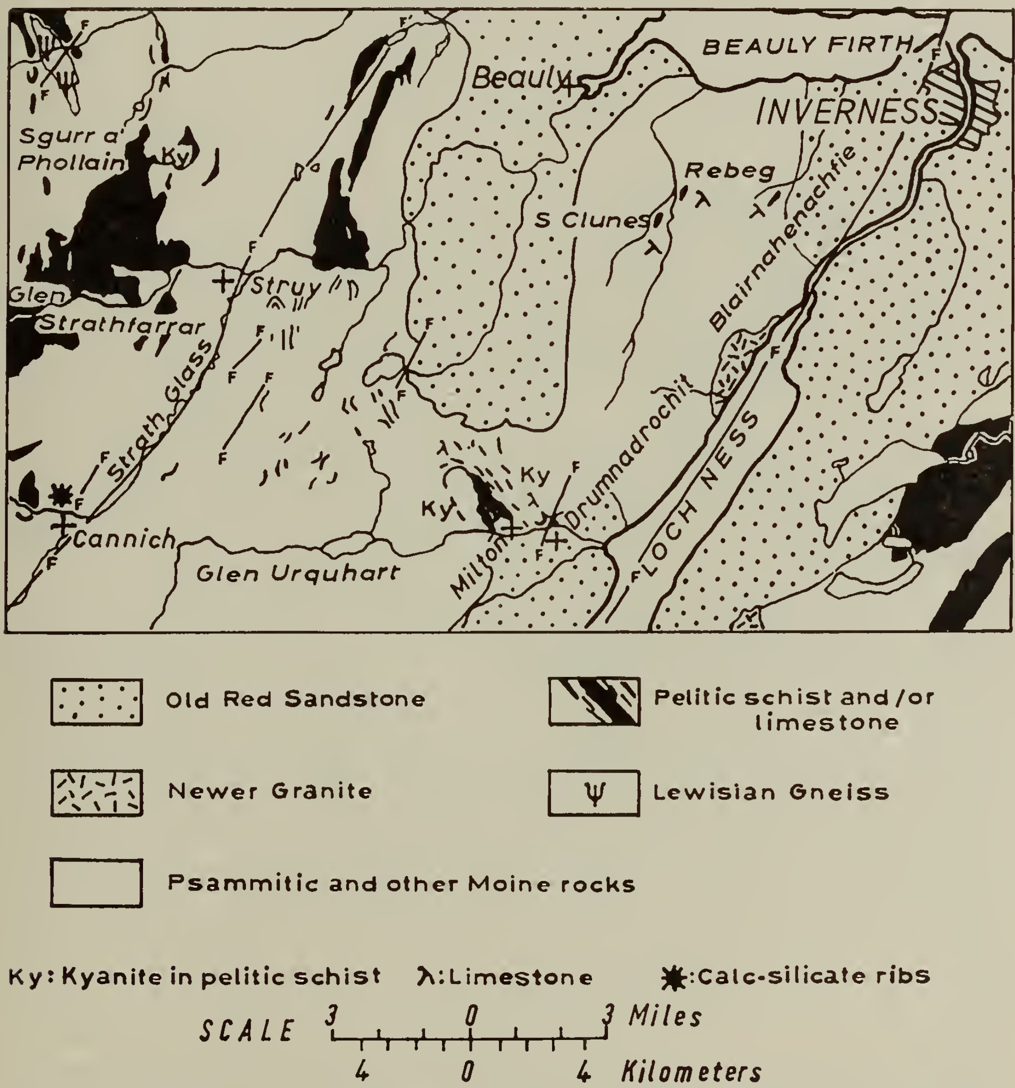


Fig. 1. Sketch map of the country around Glen Urquhart, adapted from one-inch Geological Survey of Scotland Sheet No. 83 and the writer's work.

reappear (for structural reasons) in Cunningham Craig's Moine ground. The Moine Limestones seven and a half miles to the north-east may be the analogues, if not the equivalents, of the Glen Urquhart limestone (Text-fig. 1). Like the Glen Urquhart limestone, they are invested by calc-silicate skarns of comparable mineralogy and structure.

It is now necessary to describe the kyanite-schist and psammitic gneiss in detail, both before and during the process of injection, to consider their structures and to discuss the conclusions, briefly outlined above, which may be drawn from the study.

(*b*) *The rock formations at the onset of alkali metasomatism*

(1) *Kyanite-schist*

Cunningham Craig wrote of this bed as follows :

> " At the top of the limestone the calcareous rock becomes very impure and rapidly passes into a rusty mica-schist, in which bladed or feathery crystals of pale green tremolite are often conspicuous. This soon disappears . . . and a highly micaceous, rusty-weathering gneiss appears. This band varies considerably in mineralogical composition in different localities, but the normal type is a coarsely crystalline muscovite-biotite-gneiss with large crystals of kyanite . . . quartz is also present in considerable quantity, forming a clear crystalline groundmass, and specks of pyrites are scattered through the rock. In the most highly crystalline specimens the micas and kyanite are developed at all angles to the direction of foliation, which is very indistinctly marked. In other beds the micas form a more regular felt, and large aggregates of kyanite are scattered throughout the rock, and stand out from weathered surfaces."

In thin sections graphite is seen to be present, as he remarks, and also shimmer aggregates of white mica. The micas are intimately intergrown, and contain some iron-ores.

No mention of plagioclase or garnet is made in his account although the former is almost always, the latter usually present. The rusty ochreous staining is characteristic of this horizon and helped greatly in the mapping of the bed. South of Lochan an Torra Bhuidhe, in ground almost completely unaffected by alkali injection, but where quartz veins are still quite common, kyanite has been accumulated from the surrounding schists and concentrated in the quartz veins. The mineral is bladed, limpid blue in colour and reaches 3 cm. in length. Kyanite also occurs in the surrounding schists, but only in small and scattered crystals. It is an open question whether these quartz veins originated from the centres of injection some distance to the east, or whether they are local " sweats " from the beds in which they are found. Perhaps all the veins and pegmatites, considered on a larger scale are " sweats ", in which case any distinction amongst them is unreal. The quartz-kyanite veins here are in many ways similar to those of Unst described by Read (1933), and by many other workers from various parts of the world. Miyashiro's discovery (1951) of druses in Korean quartz-kyanite veins, containing idiomorphic quartz, muscovite, and kyanite, is most significant. It strongly suggests a lack of shearing stress in the growth of kyanite, earlier accepted as the most characteristic " stress mineral ". That shearing stress is not essential to the formation of kyanite in nature is now further suggested by its recent artificial synthesis without stress.

Kyanite. This occurs in the schists in crystals from 0·2 mm. to 3·5 cm. in length. These bladed crystals show (100) and (010) cleavages, with the appropriate faces, and a well developed (001) parting. Twinning with (100) as composition plane is common, and the axis of these twins is usually normal to (100), but occasionally parallel to *b* or *c*. Sections cut normal to (100) show an extinction angle, $\gamma \Lambda c$ near 30°. There are quite a number of warped crystals, and others, cut parallel to (100), show no (010) cleavage, giving the mineral an unfamiliar look. It is then the clear, oriented biaxial negative interference figures that such sections possess which identify them with their well-cleaved neighbours and exclude the possibility of their being staurolite. The negative optic axial angle of these crystals is 82°, measured in white light.

Plagioclase. This is the sole feldspar of the uninjected kyanite-schist. The majority of grains lie between $\frac{1}{2}$ mm. and 5 mm. in size. During subsequent re-crystallization they may reach 2 cm. in greater dimension. The crystals are strongly zoned (between An_5 and An_{40}), and in uninjected rocks they are quite fresh. No saussurite or coarse epidote can be found in these rocks. The plagioclase is often twinned after the albite and pericline laws, but more complex twinning is inconspicuous and optically untwinned feldspars are common.

Almandine. Some of the physical and chemical properties of the garnet in the kyanite-schist have been determined and are given in Table III, below. In uninjected kyanite-schist the garnet is idioblastic or subidioblastic, 0·1 to 4 mm. in diameter. It is always cracked, and trains of inclusions (quartz, plagioclase, biotite, pyrite, rutile and zircon) may be found in these crystals. The garnet is always bright ruby red in the mass, but grey, with perfect isotropy, in thin section.

Muscovite. White mica grows in well-crystallized plates from 0·1 to 1·5 mm. diameter and up to 0·4 mm. deep. It is optically negative with a small optic axial angle and normal birefringence.

Biotite. This mica is abundant in the kyanite-schist. Its plates, which may be well crystallized or ragged, are from 0·1 to 3 mm. across. There are pronounced pleochroic haloes about zircons included in this mica, and the individual rings formed by various radioactive constituents of the zircon may sometimes be distinguished. Iron ore and graphite are also commonly included in the biotite. In garnetiferous rock the biotite has the pleochroism : α, straw ; β, γ, rufous red. In garnet-free rocks its pleochroism is : α, pale straw ; β, γ, earthy brown. The refractive index of the former type, β_{Na}, is 1·624, that of the latter, β_{Na}, is 1·613 (both $\pm$0·002). The chemical analyses and densities of two biotites from the two rock types are given in Table I.

Quartz. In the kyanite-schist quartz is inequigranular, and has a marked tendency to segregate into veins and knots. Microscopic inclusions, which are common, give the mineral a " hairy " appearance when examined under high magnification.

TABLE I. *Analyses and Properties of Biotites*

	1	1a		2	2a	
SiO_2	36·3	2·723	4·00	38·0	2·766	4·00
Al_2O_3	20·6	1·277 / 0·544		19·5	1·234 / 0·435	
TiO_2	2·1	0·118	2·89	1·8	0·099	2·87
Fe_2O_3	n.d.	—		0·7	0·039	
FeO	18·8	1·179		15·2	0·924	
MgO	9·4	1·050		12·6	1·366	
MnO	tr.	—		0·09	0·006	
CaO	n.d.			nil.		
Na_2O	0·3	0·044	0·91	0·3	0·042	0·74
K_2O	9·1	0·870		7·5	0·697	
H_2O+	3·6	1·800	1·80	4·2	2·039	2·09
H_2O-	n.d.			0·1		
F	n.d.			0·2	0·046	
	100·2			100·2		
less O ≡ F	—			0·1		
	100·2			100·1		
D (±0·02)	$D^{20}_4 = 3·05$			$D^{22}_4 = 2·91$		
A.	22·6			23·8		
K.	21·7			17·8		
F.	29·4			23·6		
M.	26·2			34·8		

1. Biotite from garnet-kyanite-biotite schist five-eighths of a mile north of Milton and 160 ft. north-north-east from B.M.490.0 on Kiltarlity road, Glen Urquhart.
2. Biotite from kyanite-biotite schist, ca. 400 ft. south-east from B.M.888.7 and 425 ft. north from B.M. 871.1, east side of Torr Buidhe, Glen Urquhart.
Column (a) for each analysis represents cations per 24 (O, OH, F). Both analyses by A. A. Moss.
A.K.F.M.:—co-ordinates indicating the position of the analyses in fig. 3 (X, Y).

The accessory minerals of the rock are staurolite, apatite, rutile, zircon, pyrite, magnetite, graphite and chalcocite. The pyrite is abundant, and zircon is very commonly found at the centres of pleochroic haloes in biotite. Chalcocite, which was isolated in a powdered sample of the rock, was identified by X-ray powder photography.

Three parageneses have been found amongst the kyanite-schists : (1) kyanite-quartz - muscovite - biotite ; (2) kyanite - quartz - plagioclase(An_{5-35}) - muscovite - biotite ; (3) kyanite - quartz - plagioclase(An_{15-40}) - almandine - muscovite - biotite, together with the accessories listed above. Text-fig. 4a and Plate 12, fig. 1 illustrate unaltered kyanite-schist ; kyanite and almandine are present in fresh, porphyroblastic crystals, biotite and muscovite crystallize in tablets and plates of a smaller size, the biotite containing zircons invested with pleochroic haloes. The marked lack of alteration in the minerals of this rock is worthy of note. The feldspar is not saussuritized, the kyanite is not mantled by shimmer-aggregate white mica, nor are biotite and almandine in the least altered to chlorite.

(2) *Psammitic gneiss*

Cunningham Craig described this bed as follows :

> " At a still higher horizon " [above the kyanite-schist] " the rocks become still more felspathic and quartzose . . . the separation of the minerals into well-defined laminae or lenticles, up to half an inch in breadth, becomes a conspicuous feature, while the high state of crystallization is maintained. Small dark lenticles of hornblendic material are occasionally included in the felspathic gneiss and are not infrequently drawn out into ill-defined bands which shade off into the surrounding rock."

The delicate and persistent parallel banding of quartz-feldspar and mica layers is very noticeable. It runs parallel to the sedimentary junction between this bed and the kyanite-schist below, and may be taken to mark the original bedding of a sediment. Garnet porphyroblasts are common in the uninjected rock ; they are usually smaller than 1 cm. but may reach 3 cm. in diameter. Mica varies from relative abundance (semipelitic rock) to comparative scarcity in the thinly-banded quartz-feldspar rock. This latter rock is the " granulite " of the Geological Survey's usage, indeed Harker (1932) has chosen specimens from Glen Urquhart to illustrate this type of rock, but he did raise objections to the term granulite used in this way, and Turner (1948) has done so as well. Although this meaning is entrenched in Scottish literature it does not accord with international usage and ought not to be continued. Leaving aside the French usage (meaning muscovite granite), due to Michel Levy, the general understanding of the term is quartzo-feldspathic rock within the granulite facies of Eskola. The rocks called " granulite " in Scotland are one or even two facies lower in the scale of regional metamorphism than this. Their dark minerals are distinct ; biotite being typical of the Scottish rock, hypersthene of the type used to designate the granulite facies. In view of the universal employment of the facies classification today the use of the term as in that classification is much to be preferred.

Identical white psammitic gneiss, with a sprinkling of garnets, and with oligoclase as the only feldspar, forms the bulk of the country rock along both sides of Glen Urquhart, and appears to extend (with subordinate pelitic bands) from the River Glass and the Beauly Firth in the north at least to Glen Moriston in the south. Introduced potash feldspar is very common in this tract, but it normally gives clear evidence of its late arrival by its mantling and embayment of the plagioclase, and by the formation of myrmekite at the replacement sites.

The streaks of hornblendic rock mentioned by Cunningham Craig, and thought by him to be a criterion for Lewisian age, are not in fact restricted to his Lewisian area, but continue sporadically into the Moine ground. Between Loch nam Faoileag, Loch nam Bat and Loch na Bà Ruaidhe every gradation from lenticles through small to large sills, both garnetiferous and garnet-free, can be seen. Bigger sills of amphibolite with identical macro- and microscopic appearance outcrop at the road to Kiltarlity and beyond, and also south-east of Garbeg Farm, and at Cnoc à Bhuachaille, above Balmacaan House, south of the Glen. The reason for a belt of apparently almost amphibolite-free gneisses between the " Lewisian " and the above amphibolite exposures is that the intervening ground is mostly highly injected. Even in this ground, however, small relict amphibolite lenticles, partially biotitized, can occasionally be found.

Quartz. In the Glen Urquhart rocks quartz forms an even-grained granoblastic aggregate ; the grains have sigmoid boundaries and are mostly about 0·6 mm. across ; some crystals up to 2 mm. occur. Strained extinction is common but not universal in this mosaic.

Feldspar. When the rock shows no signs of alkali metasomatism the feldspar is always a calcic oligoclase, growing with the quartz as part of the same granoblastic aggregate, and generally having a similar grain size. Whilst potash feldspar appears as a primary mineral in many Moine psammitic rocks it does not so appear in Glen Urquhart. The slide figured by Harker (1932, fig. 120A) can be studied in the Harker Collection (No. 22,358) at Cambridge. In it can be seen mantling and embayment of rotted plagioclase by fresh microcline, and the formation of myrmekite ; these relationships strongly suggest potassic metasomatism of originally more sodic rock. The feldspar of the uninjected rock is white in the hand specimen. Under the microscope it appears saussuritized, sometimes enclosing epidote coarse enough to be recognized without difficulty. It may grow preferentially along twin individuals in the plagioclase crystals.

Almandine. The garnets are subidioblastic, reaching 3 cm. across, but normally they measure no more than 4 mm. In hand specimen these crystals are brownish-pink ; in thin section they show inclusions of biotite altering to chlorite, quartz, feldspar (rare), rutile, and ore dust. The refractive index of a garnet from these rocks was found to be 1·801 ($\pm$0·003), in sodium light. It is similar to that of garnets from the kyanite-schist, and, like them, this garnet is apparently rich in almandine.

Micas. Muscovite occurs as flakes $1\frac{1}{2}$ mm. across, and in all sizes down to fine sericite after plagioclase. Biotite can exceed muscovite in quantity, but it does not always do so. It is found in plates, shreds and flakes $\frac{1}{2}$ mm., occasionally rising to 1 mm. across. The pleochroism is typically α, pale straw ; β, γ, red-brown. A garnet-biotite-muscovite-plagioclase-quartz rock has a biotite with refractive index β_{Na}, 1·618 ($\pm$0·002), whilst a similar rock which contains no garnet has a biotite with refractive index β_{Na}, 1·634.

Epidote. This occurs in the saussurite and other coarser crystals and is pleochroic from yellow to colourless. It is optically negative, and shows the typical, anomalous interference colours Berlin blue and lemon yellow.

Accessory minerals. Rutile and zircon are sometimes abundant accessories. The latter is always fresh and rounded, without metamict alteration ; it is usually seen in pleochroic haloes within the biotite. Magnetite, and occasionally ilmenite are present. Garnet and biotite show incipient chloritization in some slides. The chlorite thus formed is optically negative and shows anomalous blue interference colours. Apatite may sometimes be found.

The paragneiss has been found in three mineral combinations : (1) quartz-plagioclase(An_{25}) - muscovite - biotite ; (2) quartz - plagioclase(An_{28}) - muscovite -

biotite - chlorite ; (3) quartz - plagioclase(An_{28}) - almandine - muscovite - biotite - chlorite.

(3) *Chemical composition of the two rock groups*

The kyanite-schist (Table V. I) has the chemical composition of a clay or silt with relatively high alumina and silica. None of its oxides is outside the respective composition range for unaltered clays. The earlier stage of injection in a zone of regional metamorphism is usually one of soda metasomatism, yet in this case soda is low both absolutely, and relative to potash. This latter condition, we may remark, is characteristic of unaltered clays. Magnesia is sometimes pictured as migrating early, in a metamorphic pile, to form the " basic front " in an outermost zone of fixation and concentration. This, too, cannot be inferred from the magnesia figure which is low, and characteristic of clays.

The psammitic gneiss (Table V. V) is chemically a typical subgreywacké according to the definition of Pettijohn (1949). Its silica content places it above true greywacké and below orthoquartzite. The alumina, magnesia, and iron oxides figures agree with those of other subgreywackés. There is no apparent significance as to which of the two alkali metals is dominant ; soda considerably in excess of potash as in Glen Urquhart, can be found in recognized subgreywackés. Soda and potash together are, in the present case, within the subgreywacké range. Soda metasomatism can hardly be invoked at any event, for this bed is folded together with the kyanite-schist, which, as we have just seen is very low in soda. Turner (1948, p. 116) has commented on the general difficulty of distinguishing sodic greywackés from soda-injected schists.

As these two beds apparently possess the same chemical compositions (apart from water content) as they did before metamorphism they are *ectinites* in the sense of Roques (1941), that is rocks that have apparently been metamorphosed isochemically in a regional orogenic setting, a setting into which alkali metasomatism has never penetrated. It is worth emphasizing this situation. The Glen Urquhart rocks have undergone profound recrystallization and neomineralization raising them to the penultimate zone of Barrow's Series (Francis, 1956b), or well into the higher-grade half of the field of regional metamorphism (the granulite facies included), and this without apparent bulk chemical change other than dehydration.

Amongst those who accept regional metamorphism and granitization as parts of one process, not two distinct things, there is the belief that chemical changes begin at the moment metamorphism begins, and that they continue, unwaveringly, towards the final goal, granite. Lapadu-Hargues (1945) has assembled and grouped metamorphic rock analyses from rocks of various ages and worldwide distribution to support this view.[1] He assembled his rocks into the following groups : I Unaltered shale ; II, Muscovite phyllite ; III, two-mica schist ; IV, two-mica gneiss ; V, granitoid gneiss ; VI, granite ; VII, muscovite granite. The resulting figures are reduced to those for average rocks in each group. This reduction shows an overall trend, but obscures a noteworthy minority of cases in which steady

[1] This speculative and thought-provoking paper by Lapadu-Hargues has been much reviewed and quoted. A recent review of it is contained in Engel and Engel (1958).

chemical transition towards granite does not obtain. One may not unreasonably call in question Lapadu-Hargues' sampling methods. Mere inspection of the names of his groups shows that they trend rather directly towards granite. His object seems to be a demonstration that allochemical metamorphism exceeds isochemical metamorphism in regional terrains, yet isochemical metamorphism of pelitic rock is specifically barred from his groups V, VI and VII. However, his alkali/alumina plot (1945, fig. 1) shows, for example, that a pelitic rock with, say 4·5% mol. total alkalis, 12·0% mol. Al_2O_3, could be present in any of his groups I–IV without change in these constituents.

Metamorphic granite may form over a very wide range of pressure and temperature from the epidote-amphibolite facies to the granulite facies (Ramberg, 1949), and the adjacent sedimentary formations may recrystallize over the same range (together with the green-schist facies). But whereas in one terrain, the sediments may show steady chemical and metamorphic facies transitions towards the composition and facies of a granite massif, in other terrains (e.g. Glen Urquhart) the sediments may have been raised to a medium or high facies isochemically only to go over to

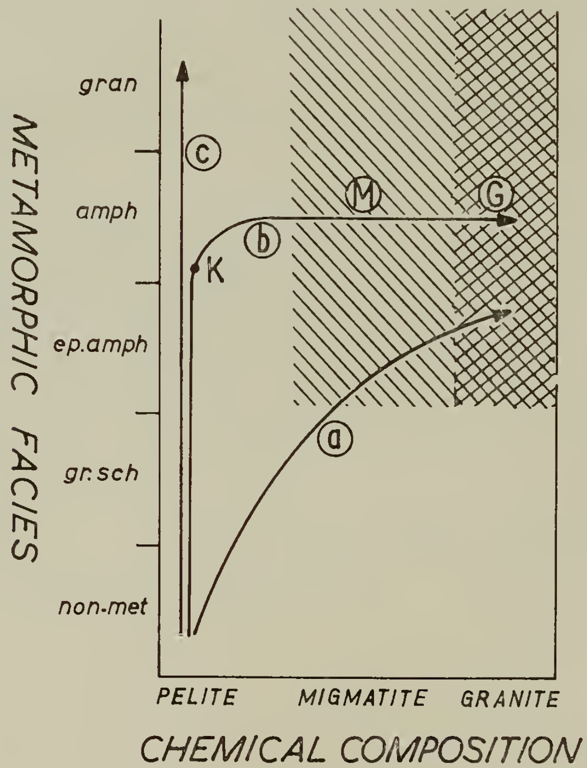


Fig. 2. Trends in metamorphic transition from pelite to granite : (a) Trend based on average compositions according to Lapadu-Hargues (op. cit., 1945). (b) Trend observed in Glen Urquhart : K = uninjected kyanite-schist. (c) Isochemical trend.

granite, thereafter, with rapid transition. In others again pelitic rock may locally reach a condition high in the granulite facies without chemical change (Ramberg, 1949 : Eskola, 1952).

Text-fig. 2 is an attempt to state these ideas graphically. Trend *a* represents Lapadu-Hargues' averages, trend *b* could be represented by the Glen Urquhart rocks with the uninjected kyanite-schist at the point K ; trend *c* is the rare one represented by granulites with the chemical composition of pelites (minus volatiles). All gradations between these cases can be envisaged.

These studies, taken by themselves, can offer no help in tracing the source of heat and pressure in regional metamorphism. Either the heat and the pressure come from granite in the heart of the orogen or they arrive by a regional raising of the isogeotherms accompanied by the pressures of mountain-building movements. Trend *a* links rising metamorphism somewhat closely with granite, trend *c* does not.

(4) *Metamorphic facies of the two rock groups before injection*

The metamorphic grade of the kyanite-schist has already been examined (Francis, 1956b) and determined to be within the kyanite zone of Barrow, or more generally, within the almandine-amphibolite facies as now defined by Fyfe, Turner and Verhoogen (1958). The grade of the limestone bed is the same (Francis, 1958).

The biotites of the pelitic and the psammitic rocks are interesting because their chemical compositions have been determined (1) by the metamorphic grade, namely the temperature, pressure on the solid phases, and pressure on the fluid phases at the time of crystallization ; (2) by the original composition of the sediment, which determines the minerals with which the biotite must share its chemical components, and with which it must grow.

In the kyanite zone assemblages of Glen Urquhart biotite frequently shares its chemical components with garnet, and the garnet in this zone (as indeed in lower zones containing the mineral) is near almandine in composition. This mineral normally has a lower MgO/FeO ratio than the rock, whilst the co-existing biotite takes up the excess magnesia by having a higher MgO/FeO ratio than the rock, moreover at a definite MgO/FeO ratio in the biotite series garnet becomes unstable and garnet-free kyanite schists with magnesian biotites are found amongst the pelites.

These relationships can be represented on the AKFM plot (Text-fig. 3) where in the general case schist compositions can fall within four tetrahedral fields (or pseudo-tetrahedral fields reduced by one phase as a result of solid solution in the biotite series) namely :

(1) kyanite—almandine—muscovite—X	with
(2) kyanite—muscovite—[X—Mg biotite]	plagioclase
(3) almandine—muscovite—[X—Fe biotite]	and
(4) microcline—muscovite—[Mg biotite—Fe biotite]	quartz

In this list X stands for the biotite composition which limits the stability of almandine.

The triangular plane between muscovite and the biotites (two phases only, because of biotite solid solution) is of great interest. It separates schists with excess

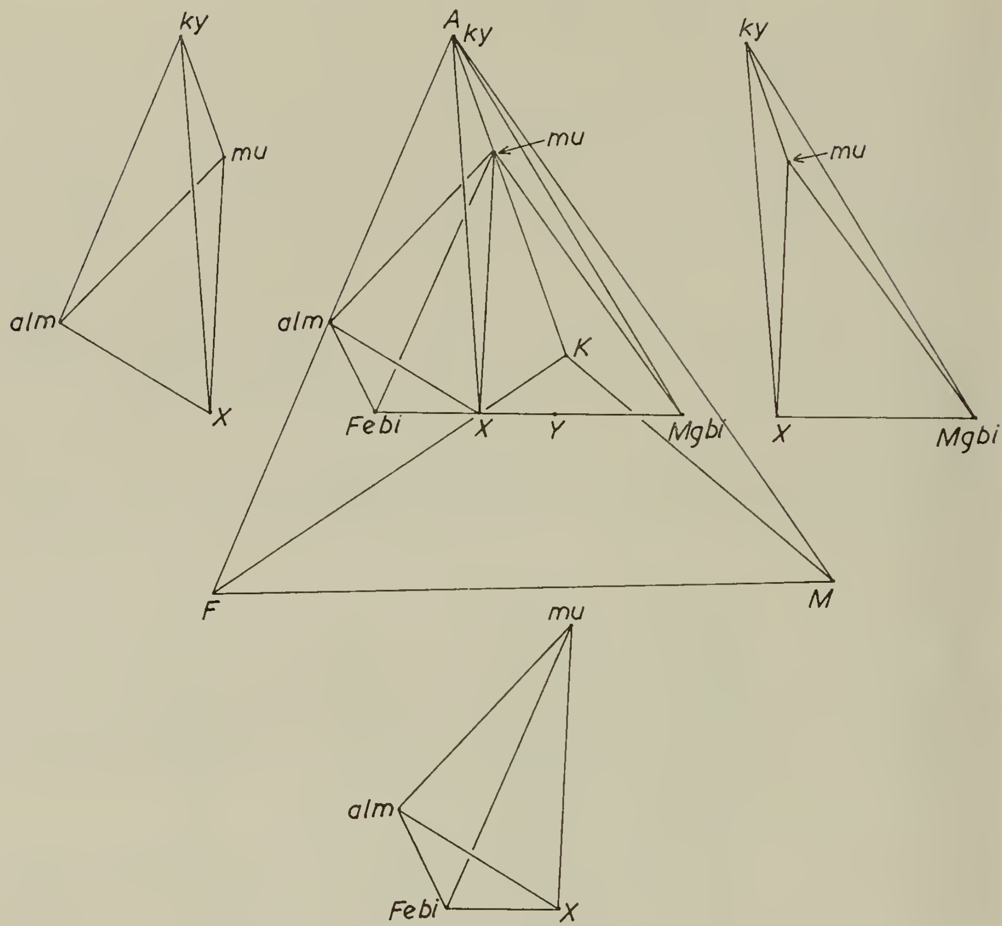


FIG. 3. (a) The AKFM tetrahedron for biotites in pelitic schists. (b) The kyanite-almandine-muscovite field. (c) The kyanite-muscovite-Mg-biotite field. (d) The muscovite-almandine-Fe-biotite field.

potash (containing microcline) from those with the excess alumina minerals almandine and kyanite, and its assemblage :

(5) muscovite—[Mg biotite—Fe biotite] – with plagioclase and quartz

does represent a number of actual rocks (microcline-free mica-schists) even though it represents (quartz and feldspars apart) the particular case of rocks plotting exactly upon a 3-phase triangle within a 4-phase tetrahedral plot.

Rocks of assemblage (5) occur amongst the psammitic gneisses at Glen Urquhart. The two analysed biotites from pelitic schists in Glen Urquhart are represented at X(paragenesis (1)) and at Y(paragenesis (2)) in text-fig. 3. Biotite X has the critical composition limiting the stability of biotite co-existing with almandine at this grade. The biotite from garnet-free kyanite schist in the Ross of Mull quoted by Lambert (1959) from the thesis of Dr. W. S. Mackenzie is represented by the point Z.

The biotites in psammitic gneiss in Glen Urquhart have not been separated for analysis because they are present in very small amounts in these rocks. Bearing in mind, however, that variations in alumina content affect refractive indices of biotites very little (Winchell, 1951, fig. 257) their MgO/FeO ratio may be reasonably foretold by their refractive indices. The biotite of psammitic gneiss with garnet (paragenesis (3)) has $\beta_{Na} = 1{\cdot}618$, that of the gneiss without garnet (paragenesis (5)) has $\beta_{Na} = 1{\cdot}634$.

It is clear, as observation of text-fig. 3 will confirm, that as between two kyanite-free rocks of like MgO/FeO ratio an almandine-free rock will have a more iron-rich biotite than the almandine-bearing rock. It therefore appears that the above-mentioned pair in Glen Urquhart may come from rocks of approximately the same MgO/FeO ratio. (If the MgO/FeO ratios of the two sediments were divergent there would be no bar to the formation of a magnesian biotite in the almandine-free psammitic gneiss.)

We arrive, then, at the interesting position that where kyanite is present the almandine-bearing rock will contain a *more ferrous* biotite than the almandine-free rock, whilst where kyanite is absent (and providing MgO/FeO ratios of the rocks are close together) the almandine-bearing rock will contain a *more magnesian* biotite than the almandine-free rock ; which is the position in Glen Urquhart. The polymetamorphic pelitic schists of Mayurbhanj, India, contain an early (regional metamorphic) assemblage : quartz, muscovite, biotite, garnet, staurolite, kyanite, ore, according to Naha (1956). The grade of this assemblage is probably slightly lower than that of Glen Urquhart, that is, it belongs to the staurolite zone (c.f. Francis, 1956b). The biotites of these schists must be of a definite composition, as is biotite X in assemblage (1), (Text-fig. 3), and their refractive indices (1·666 to 1·671) and strong red-brown colours indicate that they are iron-rich. The composition X therefore appears to become progressively more magnesian with rising grade in kyanite-garnet-muscovite-biotite schists, as indeed might be expected.

This transition in biotite compositions is, however, over a rather limited P–T range in a particular rock type. Lambert's suggestion (1959 p. 565) that MgO/FeO ratios of biotites in psammitic and pelitic schists as a whole should increase with rising regional metamorphism is too sweeping. The influence of original composition of the rock (expressed by presence or absence of kyanite, garnet and other FeMg silicates) must blur the overall changes brought about in schist biotites by changing temperature and pressure alone. The range of mean refractive indices in the biotites of the almost isometamorphic schists of Mayurbhanj, Ross of Mull and Glen Urquhart (1·671 to 1·613) is greater than the whole range of refractive indices of schist biotites from the biotite zone to the kyanite zone (1·656 to 1·616) given by Lambert.

ALKALI METASOMATISM

(*a*) *The Evidence of Metasomatism*

The area described in this paper shows every transition from the schists and gneisses already described, with the chemical composition of pelitic and psammitic sediments, through all gradations of feldspathic impregnation and the suppression

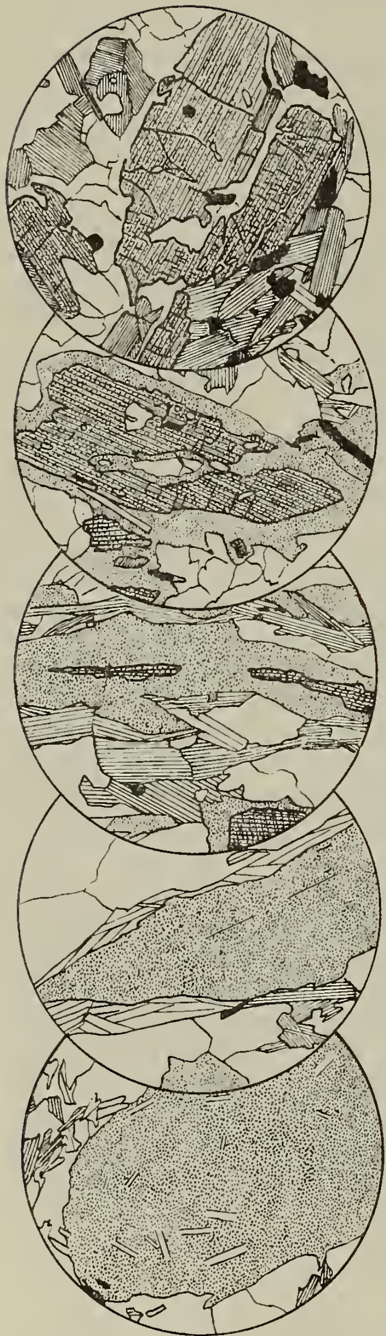


FIG. 4. Progressive metasomatism of kyanite-schist (× 21):

(a) Unaltered kyanite-schist (see also Pl. 12, fig. 1).

(b) Metasomatized kyanite-schist, showing relics of kyanite mantled by " shimmer-aggregate ".

(c) The same, a more advanced stage.

(d) The same, converted to migmatite (see also Pl. 12, fig. 2).

(e) Kyanite-schist from the Moine area (of Cunningham-Craig), with kyanite completely replaced by shimmer-aggregate.

of excess alumina minerals to the final state of a microcline-plagioclase-quartz rock with subsidiary muscovite, that is, a leucogranite. There are no sharply-defined boundaries anywhere in this transitional series. The bedding-plane foliation of the schists passes through unaltered rocks, impregnated rocks and even the granitic rocks without obliteration or deflection of strike. The granitic areas, which are chemically the most divergent from the composition of the unaltered sediments, seem to be the foci of the arrival (presumably uprise) of the feldspathizing fluids ; and the degree of feldspathization increases regularly towards them.

The injection phenomena at Glen Urquhart are almost entirely permeative. In hand specimen and under the microscope one can study the arrival of alkali feldspar throughout the groundmass of the rock. Lit-par-lit injection gneisses are quite subordinate to the permeation gneisses.

The injection is accompanied by pegmatites and quartz veins, which are common at the granitic centres, and which decrease in numbers towards the uninjected rocks. No doubt these veins played a part in distributing the feldspathizing fluids through the rocks. The pegmatites are narrow straggling veins (not above 30 cm. across), whose margins do not correspond to one another in shape, and indeed sometimes shade off into the surrounding migmatite. The mineralogy of the pegmatites is simple, and corresponds to that of the rocks they traverse. They contain glassy quartz, white or pink sodic feldspar, pink microcline and " books " of muscovite or biotite. The crystals range from 0·5 to 3 cm. across with fine granular crystals between the large ones. Some of the quartz veins far out amongst the uninjected rocks have picked up other minerals from the wall rocks, such as kyanite, in the case discussed earlier in this paper, and also epidote and other skarn minerals, where the veins traverse limestone and calc-silicate rocks (Francis, 1958). Where kyanite-schist is the host rock the kyanite is soon destroyed by the injection and replaced by white mica. It is then that the ochreous staining of this bed becomes important in mapping its prolongation into injected ground. In a few useful cases pseudomorphs of shimmer-aggregate white mica after kyanite appear on weathered surfaces and help mapping of the injected kyanite-schist. Under the microscope corroded cores of kyanite within these pseudomorphs can be found in the outermost zones of injection (Text-figs. 4b, c).

There is a perfect transition through all stages from fresh kyanites to kyanites completely replaced by white mica in the pelitic rocks. All stages in the alteration can be traced within the ground mapped as Lewisian by Cunningham Craig (1914). The pseudomorphs in which all kyanite has been resorbed lie close to his line of unconformity, and beyond it in Cunningham Craig's Moine ground, in a few scattered localities, identical pseudomorphs have been found in injected pelitic rocks. One such rock in the Moine (Text-fig. 4e) lies 1,610 yards from the nearest point of Lewisian as mapped by Cunningham Craig. The pelites on either side of Cunningham Craig's unconformity are linked not only by kyanite on the one side to pseudomorphs after kyanite on the other, but also by almost identical garnets in each pelite as will be shown.

The pelite may sometimes pass from the stage with pseudomorphs after kyanite alone into one in which all feldspar is temporarily resorbed, and a rock rich in white mica develops. In this rock the pseudomorphs after kyanite are still distinct. Later, a sodic feldspar re-appears, sometimes as white augen, in other cases with a red colour and more permeative growth. The feldspar of pegmatites in this zone is also sodic.

With further injection red microcline appears. Thin sections stained with cobaltinitrite demonstrate the gradual mantling, embaying and replacement of soda by potash feldspar and the accompanying formation of myrmekite at this stage. Garnet is attacked in this potassic environment, and converted into biotite (Pl. 11, figs. 2, 3). At this stage of injection it is only in rare cases that patches of migmatized kyanite-schist, " pelitic ghosts ", can be recognized and mapped as such. A much larger amount of kyanite-schist is no doubt mapped with psammitic gneiss in the migmatite areas of the map (Pl. 14).

Where psammitic gneiss is the host rock there is an early introduction, or more probably, redistribution, of sodic feldspar, usually red in colour, soon followed by red microcline, often in fine-grained permeative manner, with the same replacement of sodic feldspar, and the same myrmekite growth as in the pelite.

From the stages reached above the two rock types pass through thoroughly potassic migmatites to granite gneisses. Several repetitions of the two rocks by folding can often be traced along strike into one granite gneiss centre, demonstrating the convergence of the two initial materials upon a single end product.

The Glen Urquhart injection sequence is unusual in that soda metasomatism is subordinate to potash metasomatism throughout. The soda metasomatism appears to be no more than a redistribution of existing plagioclase by the fluids active at the outer limits of the injection. By contrast, in some of the classical injection complexes, e.g. Cromar (Read, 1927), Central Sutherland (Read, 1931), and Stavanger (Goldschmidt, 1921), a marked soda metasomatism precedes a relatively minor potash metasomatism.

(*b*) *Minerals of the injection rocks*

Many of the pre-injection minerals, already described, remain in the schists to a quite advanced stage in the migmatization. For the most part, only the new minerals of the injection rocks will here be described.

Feldspar. The introduced or redistributed plagioclase may be as calcic as andesine (An_{40}) but it is usually oligoclase. Most of it is pink in the mass and turbid in thin section. Sericitization is very common, especially in the plagioclases of pegmatites. (Chloritization of biotite, which occurs in the outer zones of the injection, may provide enough potash to form this sericite.) Augen of plagioclase up to $\frac{1}{2} \times 3$ cm. grow in some migmatites, whilst in the pegmatites feldspars up to 4 cm. in greatest dimension can be found.

Potash feldspar occurs in pegmatites close to the injection centres, and in the rocks at or near these centres. Cobaltinitrite staining shows that it first appears as infiltrations along cracks and cleavages in pre-existing plagioclase. In some cases the potash feldspar has replaced one set of albite twins whilst the other set remains as plagioclase within a single crystal. At a later stage it mantles the sodic feldspar, and finally grows as large homoeoblastic crystals, elbowing aside the shrinking plagioclase, whilst much myrmekite simultaneously forms at grain boundaries between feldspar and quartz.

The potash feldspars from a typical Glen Urquhart migmatite have already been described by Mackenzie (1954). He writes :

> " Almost all the grains show very uneven extinction, parts of individual crystals show cross-hatch twinning typical of microcline, and other parts are untwinned. . . . A small amount of microperthitic albite is irregularly distributed in many of the crystals."

The variable lattice of this feldspar, suggested by the patchy optical properties, is confirmed in the X-ray powder spectrometer pattern (Mackenzie, 1954, fig. 5b). It indicates a large amount of monoclinic or almost monoclinic material grading into smaller and smaller amounts of feldspar with increasing departure from monoclinic symmetry.

The nature of the inversion from monoclinic to triclinic feldspars, and the types of potash feldspar normally present in regionally metamorphosed rocks are two topics that are widely discussed in the literature. The control of the inversion purely by a fall in temperature (with inversion occurring at around 500° C.) is suggested by Goldsmith and Laves (1954), but this inversion has been given a tentative chemical control by Mackenzie (1954), who suggests that it can only occur when the feldspar is, or becomes practically soda-free. Regionally metamorphosed potash feldspar rocks in Scotland, for example those mentioned by Harker (1954) and by Lambert (1959) as well as those of Glen Urquhart, contain feldspars varying structurally from orthoclase to " maximum microcline ", with patchy variation in each individual crystal. Marmo (1955), on the other hand, describes migmatitic granites from Sierra Leone and Finland which, in his opinion, grew potash feldspars which were triclinic from the beginning, and never inverted from a monoclinic condition. According to Hier (1955) perthite may form as an intermediate stage in the replacement of plagioclase by microcline rather than as a result of subsolvus exsolution of a once-homogeneous feldspar. This may be the explanation of the small amounts of perthite mentioned by Mackenzie.

Quartz. Much of the injected quartz is inequigranular and sutured. It commonly has strained extinction, particularly in pegmatites, and is " hairy " with fine inclusions in many cases.

Muscovite. White mica is abundantly introduced in the early stages of injection, particularly into the kyanite-schist. In an early stage of injection of this schist (Rock II, Table V, and Pl. 12, fig. 4) all the feldspar has been resorbed and sericitic white mica has taken its place. It has also (in the form of " shimmer aggregate ") taken the place of kyanite. The rock is now composed of 64·5% of white mica by volume. Since this white mica apparently holds all the alkalis of the rock (0·60% Na_2O, 4·43% K_2O) it should contain about 12% of paragonite in its structure. As the original kyanite-schist has a similar amount of soda (0·71%) it appears that no soda was introduced at this stage and that the white mica's soda component did indeed come from pre-existing plagioclase. Muscovite in the pegmatites grows in

" books " and plates up to 4 cm. across. Blood red hematite occurs in muscovite cleavage planes in some of the schists, as it does at Morar (Lambert, 1959).

Biotite. The biotite of migmatites and pegmatites has a darker set of pleochroic hues and a higher refractive index, than that of the majority of the uninjected sediments. No doubt this indication of a higher iron content is to be explained by resorption of almandine during injection. Whether the biotite of the migmatites will be more aluminous (as well as more ferrous) than that of the uninjected garnet mica schists is hard to forecast. If almandine is replaced by aluminous iron biotite (siderophyllite) the volume increase will be very great, if it is replaced by alumina-poor iron biotite (annite) the volume increase will be less.[1]

(I) $$2Fe_3Al_2Si_3O_{12} + K_2O + 2H_2O = K_2Fe_6Si_6Al_2O_{20}(OH)_4 + Al_2O_3$$

			Volume Increase
almandine	annite		29%
217 cc.	280 cc.		

(II) $$4Fe_3Al_2Si_3O_{12} + 2K_2O + 4H_2O = K_4Fe_{11}Al_6Si_{11}O_{40}(OH)_8 + SiO_2 + Al_2O_3 + FeO$$

			Volume Increase
almandine	50% annite 50% siderophyllite	quartz	48%
434 cc.	617 cc.	23 cc.	

(III) $$2Fe_3Al_2Si_3O_{12} + K_2O + 2H_2O = K_2Fe_5Al_4Si_5O_{20}(OH)_4 + SiO_2 + FeO$$

			Volume Increase
almandine	siderophyllite	quartz	56%
217 cc.	316 cc.	23 cc.	

These volume increases are large, but volume-for-volume replacements probably occur but seldom in alkali injection-metamorphism. The texture of the almandine-biotite replacement here considered (Pl. 11, figs. 2, 3) is not pseudomorphous and moreover biotite material may be removed from the immediate site of garnet-attack to combine with neighbouring pre-metasomatism biotite. Poldervaart (1953) has given reason to suppose that metasomatism causes volume increases in schists, and the present example shows that it is not only the formation of new feldspar which causes this increase.

Even allowing for increases in volume the more modest case in which annite is produced does seem more likely than the extreme case where siderophyllite is produced. At all events the product of biotitization of almandine must always mingle with the pre-existing biotite to form the somewhat iron-enriched mica of the injection rocks, having the optical properties set out in Table II.

TABLE II. *Biotites from injection rocks*

Rock Type	Paragenesis (Table IV)	Pleochroism	Refractive Index ($\pm$0·002 : sodium light)
Pegmatite	5	α, straw	
		β, γ, dark rufous red	1·634
Migmatite	21	α, greenish straw	
		β, γ, brownish black	1·635

[1] In calculating the volume increases in reactions I–III, fixation of SiO_2 as quartz and removal of FeO and Al_2O_3 have been arbitrarily assumed. Possibly the FeO remains as ore dust at the reaction site.

Table II (*continued*)

Granite gneiss .	18	α, greenish straw β, γ, brownish black	1·635

The granite gneiss mentioned in Table II contains a little relict almandine in process of biotitization. Biotite itself is characteristically converted to chlorite along its margins and cleavage traces at all stages of the injection. In the granite gneisses the process is almost complete. Apparently, in this increasingly potassic environment K_2O is progressively monopolized by feldspar at the expense of the micas, and small remnants of ferromagnesian material are then held in wisps of chlorite.

Biotites in the migmatites often contain prehnite growing in, and wedging apart their cleavage planes. This is a common feature of injected biotites, which has been noted by Read (1931), Drever (1940) and Cheng (1943) amongst others.

Almandine. The garnet in the migmatites and granite gneisses is always a relict mineral, but being stable in structure it is not quickly resorbed. It is never present in the pegmatites.

Small garnet samples were separated from a kyanite-almandine mica-schist and from a strongly injected pelitic migmatite. The latter contains pseudomorphs in " shimmer-aggregate " white mica after kyanite. The first rock shows the stable co-existence of almandine with biotite, muscovite and kyanite. In the second the almandine is a relict mineral under attack. The fresh garnet is idioblastic to subidioblastic, 0·1 to 4 mm. in diameter, and always cracked. The cracks are often parallel to one another, and to a crystal face. There are trains of inclusions containing quartz, plagioclase, biotite, pyrite, rutile, and zircon, but no muscovite or kyanite. The trains show a tendency towards spiral growth (Pl. 11, fig. 2). The garnet in injected pelitic schist is ragged and in process of alteration to biotite (Pl. 11, fig. 3).

Some physical and chemical properties have been determined from the separated powders of the two garnets, and they are set down in Table III.

TABLE III. *Garnets of pelitic schists : Physical constants and partial chemical analyses*

	I	II
Refractive Index		
(±0·003 : sodium light)	1·797	1·795
Specific Gravity		
(±0·05)	4·07	4·06
Cell Size		
(Å±0·002)	11·531	11·550
Fe_2O_3	0·48	0·24
FeO	31·03	32·29
MnO	0·67	1·86
Calculated percentage weight		
Almandine	71·66	74·63
Andradite	1·53	1·02
Spessartine	1·56	4·34

I. Garnet in uninjected kyanite-schist, Sgòr Gaoithe.
II. Garnet in injected kyanite-schist, Loch nam Faoileag.

These figures are in such close agreement that they could well represent two samples of a mineral formed in the same stratum after the same metamorphic history. This view is reinforced by the occurrence of the fresh garnet in a kyanite-schist, and the occurrence of the somewhat biotitized relict garnet in a pelitic migmatite containing pseudomorphs in white mica after kyanite. It is interesting, therefore, to find that the fresh garnet is in the Lewisian, and the injected garnet is in the Moine according to the mapping of Cunningham Craig (1914).

Chlorite. As already noted, chlorite forms from biotite, and it also forms directly from almandine during the course of injection. It has low birefringence and is usually optically negative, but occasionally optically positive in replacements of biotite. A chlorite after biotite in injected kyanite-schist has a birefringence of 0·001 with anomalous violet colours. It has negative elongation, and is therefore optically positive, the refractive index $\beta = 1{\cdot}583$ ($\pm 0{\cdot}002$), indicating a pennine approaching diabantite (Hey, 1954). This is probably a typical composition for these migmatite chlorites.

Accessory minerals. Zircon is almost universal in the injection rocks, forming strong pleochroic haloes in biotite. Apatite, rutile, allanite and graphite are also common. The ores are represented by magnetite (with hematite), ilmenite (sometimes mantled with sphene) and pyrite. Occasionally the injection rocks contain sporadic epidote minerals derived from recrystallization of saussurite and found also in rocks transitional to the skarns already described (Francis, 1958). With these may also be grouped rare needles of tremolitic amphibole and overgrowths of calcium silicate hydrate (xonotlite?) on feldspars.

(*c*) *Parageneses of the injection rocks*

The mineral associations of these progressively altered rocks are, not surprisingly, almost all indicative of disequilibrium, as can be seen in Table IV (in which conventional abbreviations have been used).

TABLE IV. *Parageneses of the Injection Rocks*

Pegmatite

1. qtz-plag(olig)-micr-mu-bi
2. qtz-plag(An_{14})-bi-chl
3. qtz-plag(olig)-mu
4. qtz-plag(An_{17-33})-mu-bi
5. qtz-plag(An_{23})-mu-bi-chl
6. qtz-plag(An_{30-35})-mu-chl

Migmatite and Granite gneiss : kyanite schist host

7. ky-qtz-plag(An_{15})-alm-mu-bi-chl
8. ky-qtz-plag(An_{25-35})-mu-bi-chl
9. qtz-plag(An_{32})-micr-alm-mu-bi-chl
10. qtz-plag(An_{30})-micr-mu-bi-chl
11. qtz-plag(An_{25})-micr-mu-bi
12. qtz-plag(olig)-alm-mu-bi
13. qtz-plag(An_{14})-alm-mu-bi-chl
14. qtz-plag(An_{30-40})-mu-bi
15. qtz-plag(An_{30})-mu-bi-chl
16. qtz-mu-bi-chl

Migmatite and Granite gneiss : psammitic gneiss host

17. qtz-plag(olig)-micr-alm-mu-bi
18. qtz-plag(An_{25-33})-micr-alm-mu-bi-chl
19. qtz-plag(An_{30})-micr-mu-bi
20. qtz-plag(An_{30})-micr-mu
21. qtz-plag(An_{24-32})-micr-mu-bi-chl
22. qtz-plag(An_{25})-micr-mu
23. qtz-plag(olig)-micr-chl
24. qtz-plag(An_{24})-alm-mu-bi-chl

(*d*) *Metamorphic facies of the injection rocks*

It is difficult to establish, from paragenetic studies, the metamorphic grade of the area at the time of injection. Almost all the injection rocks display disequilibrium textures and mineral associations. Some important indicator minerals in the migmatites (kyanite, garnet) are relicts from the earlier stage of isochemical metamorphism, now under chemical attack. In the new conditions which bar them chemically they are of no significance for grading purposes. The paragenesis towards which all the others are trending : qtz-plag-micr-mu (granite gneiss) is not a sensitive one for grading purposes.

The presence of muscovite, with absence of sillimanite, denotes a lower grade during this injection than in that of some other areas (c.f. Watson, 1949). Alteration of garnet and biotite to chlorite during injection could be occasioned by a shift to higher partial vapour pressure of water, rather than by a lowering of pressure on the solid phases and of temperature ; but some lowering of P and T seems likely. The grade of some of the skarns formed by the same injection episode is low, for the assemblage quartz-albite-muscovite-chlorite-calcite (typical of the greenschist facies) is recorded (Francis 1958, p. 154). Furthermore, plagioclase, often in association with some epidote tends to become slightly more sodic in the schists which have been injected.

Possibly some of the schists have descended from their pre-injection facies either to the lowest part of the almandine amphibolite facies (of Fyfe, Turner and Verhoogen, 1958) or, locally, into the greenschist facies during the injection episode. At all events the grade at the time of injection is well below the curve of fusion for water-saturated granite used by Fyfe, Turner and Verhoogen (1958, fig. 107) as the lower P-T limit for granitization. In other words, the granitization in Glen Urquhart is a hydrothermal phenomenon, as it has been found to be in the areas studied by many workers (e.g. Kullerud and Neumann, 1953, Marmo, 1955), and is not the work of a permeative, water-rich magma as generally implied by Fyfe, Turner and Verhoogen.

(*e*) *The Glen Urquhart injection series*

From amongst the many rocks studied seven have been selected for detailed examination, and they have been chosen as representing the two initial materials, kyanite-schist and psammitic gneiss ; the two trends of progressively altered rocks ; and their end product and point of convergence, migmatitic granite gneiss. They are as follows :

I. Kyanite-garnet mica-schist, from 55 yards above the road bridge, over the Allt Gartally, Kiltarlity road. Original material of the pelitic series. Paragenesis

8, Table IV ; Text-fig. 4a ; Pl. 12, fig. 1. The rock contains blades of kyanite with coarse-grained biotite and ore, together with a little medium-grained muscovite, set in a ground of quartz and fresh plagioclase (An_{30}, zoned). Zircon is present in strongly marked pleochroic haloes in the biotite. The minerals are all perfectly fresh and show no interaction. The rock is within the Lewisian on Cunningham Craig's map.

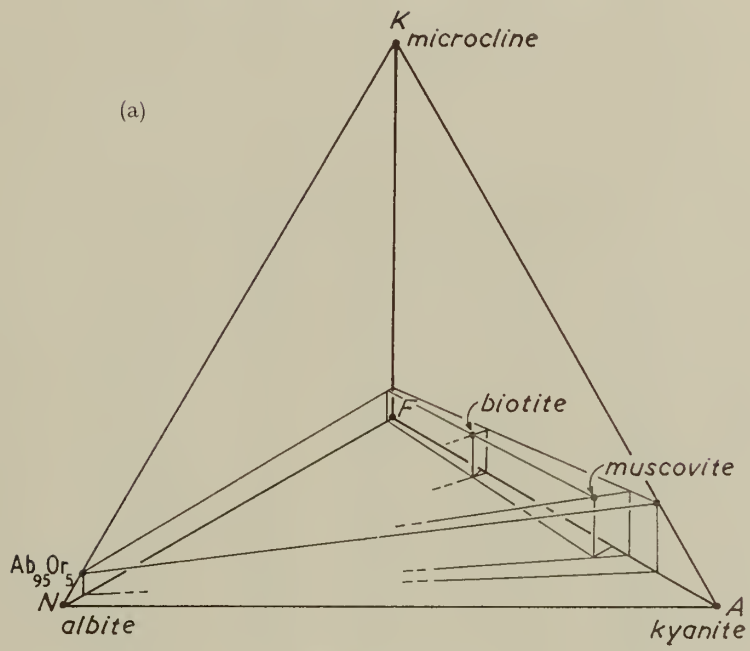
II. Pelitic muscovite-rich migmatite, from north of the drift flats of Allt an Loch Ghuirm. Kyanite schist host. Paragenesis 16, Table IV. Pseudomorphs in shimmer-aggregate white mica after kyanite are prominent ; they are always rimmed with coarser muscovite plates. In addition there are other muscovite crystals, quartz, a little chlorite and a trace of biotite, but no feldspar (Text-fig. 4d, Pl. 12 fig. 2). The rock is just within the Lewisian on Cunningham Craig's map, within a few paces of his unconformity.

III. Pelitic plagioclase-porphyroblast migmatite, from close to the top of the road cutting, valley of the Allt Gartally. Kyanite-schist host. Paragenesis 9, Table IV. Dark grey, finely-foliated, with white " eyes " elongated with the foliation. The rock is composed of abundant biotite, subordinate muscovite and chlorite and scattered garnets in a quartz-feldspar ground. The " eyes " appear to have been single plagioclases (An_{32}) but these are now largely replaced by myrmekite. Cobaltinitrite staining reveals the earliest infiltration of microcline along cracks, crystal boundaries, and cleavages in the " eyes " (Pl. 12, fig. 3). The rock is just within the Lewisian on Cunningham Craig's map.

IV. Pelitic potassic migmatite, from one-sixth of a mile south-east of Loch Maolachain. Kyanite-schist host. Paragenesis 11, Table IV. A fine-grained, highly-injected migmatite whose occasional micaceous layers suggest pelitic parentage. There is abundant microcline with wavy, ill-defined grid twinning, mantled on and eating into sericitized plagioclase (An_{25}), with much accompanying myrmekite. Quartz is polygonal in outline and has somewhat strained extinction ; muscovite and biotite are present (Pl. 12, fig. 4). The rock is in the Moine on Cunningham Craig's map, 46 yards from his line of unconformity.

V. Psammitic garnetiferous gneiss, from half-way between Cnoc na Moine and Loch nam Faoileag. Original material of the psammitic series. Paragenesis 24, Table IV ; Pl. 13, fig. 1. The rock contains subidioblastic almandine 4 mm. across, with inclusions of quartz, plagioclase (uncommon) and biotite altering to chlorite. There is less chlorite in the ground but here also it is forming after biotite. Quartz and plagioclase (An_{24}) form a granulitic mosaic, holding scattered biotite and rare muscovite ; the feldspar is saussuritized. The rock is in the Lewisian on Cunningham Craig's map.

VI. Psammitic potassic migmatite, from lower crest of Craig Achmony overlooking Kilmichael [B.M. 1955.64(24)]. Psammitic gneiss host. Paragenesis 18, Table IV ; Pl. 13, figs. 2, 3. Migmatite, in which the incoming of microcline can be traced across the slide. At one side staining shows that microcline replacing plagioclase (An_{29}) is scarce, biotite is stable, and there are a few small, somewhat biotitized garnets. On passing to the other side microcline becomes abundant, replacing



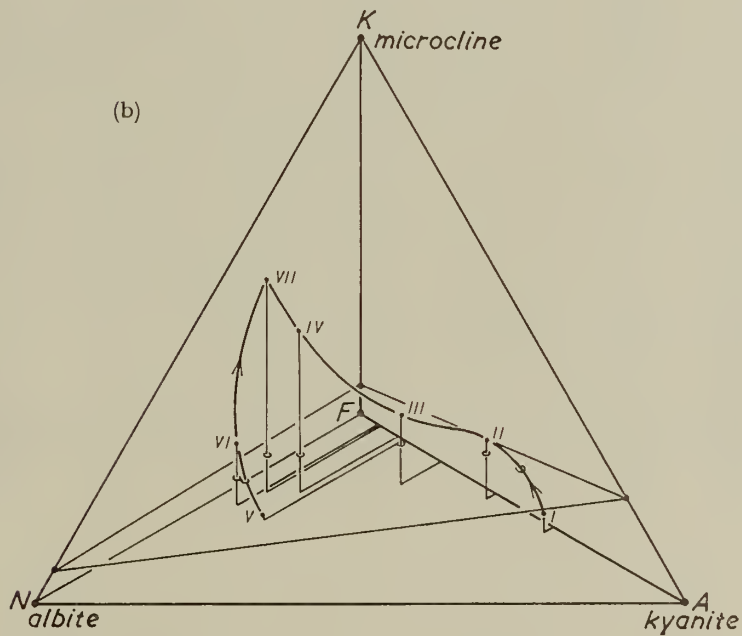


FIG. 5. The AKNF tetrahedron : (a) To show the plane of zero microcline. (b) To show the position of analyses I–VII with reference to the zero-microcline plane.

TABLE V. *Analyses of Rocks from the Migmatite Series in Glen Urquhart*

	I	II	III	IV	V	VI	VII
SiO_2	61·86	62·17	71·6	85·4	76·16	81·0	74·36
TiO_2	1·01	0·75	0·9	tr	0·55	0·5	0·55
Al_2O_3	23·76	18·62	13·4	7·7	12·11	9·2	13·53
Fe_2O_3	0·83	1·27	1·9	—	0·69	—	0·62
FeO	6·31	3·12	2·6	0·7	2·60	1·7	0·20
MnO	0·09	0·20	0·03	tr	0·01	tr	—
MgO	1·87	3·40	1·2	0·1	0·88	0·5	0·04
CaO	0·56	0·16	0·9	0·5	2·49	1·4	0·18
Na_2O	0·71	0·60	1·6	1·5	3·19	2·7	2·92
K_2O	1·85	4·43	3·9	3·2	0·37	1·5	7·11
P_2O_5	0·27	0·11	0·1	tr	0·08	tr	0·04
H_2O^+	0·68	4·77	1·7	0·5	0·36	1·0	0·64
H_2O^-	0·05	0·13	0·06	0·1	0·04	0·1	0·10
Total	99·85	99·73	99·9	99·7	99·53	99·6	100·29
D.	3·06	2·77	2·76	2·63	2·75	2·64	2·65

Trace Elements : Parts per Million

	†	I	II	III	IV	V	VI	VII
Ga	(2)	20	20	15	8	15	8	15
Cr	(1)	65	65	25	3	25	10	2
V	(5)	90	65	45	5	45	10	*
Li	(1)	10	25	10	*	2	3	2
Ni	(1)	35	10	22	5	6	10	*
Co	(5)	20	*	10	*	*	5	*
Sc	(10)	20	15	*	*	*	*	*
Zr	(10)	550	400	600	150	500	350	45
Yt	(10)	65	10	20	*	60	10	*
La	(30)	120	*	*	*	*	*	*
Sr	(5)	200	*	150	250	400	200	200
Pb	(10)	*	10	*	*	*	*	*
Ba	(5)	350	750	700	1000	50	250	1500
Rb	(10)	90	170	175	130	20	95	165

Table V (*continued*)

Modes : Volume per cent.

	I	II	III	IV	V	VI	VII
qtz	40·9	18·5	47·2	43·8	60·5	56·9	25·7
ky	26·7	—	—	—	—	—	—
staur	tr	—	—	—	—	—	—
olig	5·2	—	9·0	18·4	27·4	33·7	17·9
micr	—	—	2·9	27·9	—	2·6	50·6
alm	10·9	—	—	—	7·6	—	—
mu	1·0	a 33·9 b 31·5	23·5	2·4	0·3	2·2	5·1
bi	14·0	1·1	16·6	5·9	1·7	4·0	—
chl	—	11·7	—	—	0·8	tr	—
ore	0·4	2·3	0·3	0·2	0·3	0·5	0·7
rut	0·7	0·5	—	—	0·9	—	—
ap	tr	0·3	0·3	1·4	0·3	0·1	—
zir	0·2	0·2	—	—	0·2	—	—

Notes :
* below the limit of sensitivity for this element.
† limits of sensitivity.
a coarse muscovite.
b " shimmer aggregate " after kyanite.

I Uninjected kyanite-schist (unaltered pelitic rock).
II Muscovite-rich (injected) kyanite-schist.
III Oligoclase-porphyroblast schist (pelite).
IV Fine-grained potassic migmatite (pelitic host).
V Garnet-paragneiss (unaltered psammitic rock).
VI Sodi-potassic migmatite (psammitic host).
VII Granite-gneiss (final product).

For further details and localities of the rocks see text, pp. 187-192 and captions for Plates II and III.

ANALYSTS : G. H. Francis (I, II, V, VII) ; D. I. Bothwell (III) ; K. C. Chaperlin (IV, VI). Trace element determinations by S. R. Nockolds and R. Allen, excepting Sr and Rb which are by J. R. Butler.

most of the plagioclase, biotite is chloritized and garnet is absent. Large apatites and zircons accompany the injection. The rock is in the Moine on Cunningham Craig's map.

VII. Migmatitic granite gneiss, from just below (east of) the summit of Craig Achmony. Host may be pelitic or psammitic. End product of the metasomatic changes. Paragenesis 22, Table IV ; Pl. 13, fig. 4. Highly-injected migmatite with microclines 1 to 2 mm. across, with patchy tartan twinning and showing replacement boundaries towards subordinate, sericitized plagioclase (An_{25}). There is much accompanying myrmekite. Quartz grows in inequigranular crystals with " hairy " inclusions and having undulose extinction. There are a few shreds of muscovite. The rock is in the Moine on Cunningham Craig's map.

(*f*) *Chemistry of the injection series*

The chemical analyses of the seven rocks selected for detailed study appear in Table V, on which the trace element determinations and the volume modes of the rocks are also set down. Clearly they are no more than a reconnaissance of the variations within this belt of alkali metasomatism. Nevertheless, the trends shown by these seven analyses are reasonable pointers to the full picture because the ranges of compositions of the pelitic schist, the psammitic gneiss and the granite gneiss respectively must be small in comparison to the differences between these rock groups, spanned by the metasomatism.

The most conspicuous change in this rock series is increase in potash in both the pelitic and psammitic rocks, culminating and converging on the granite gneiss (VII). The series can suitably be represented by plots in the AKNF tetrahedron. This corresponds to the AKF triangular plot (e.g. Turner, 1948, fig. 20), with soda (N) in addition. The important join muscovite-biotite in the AKF triangle becomes a plane in the AKNF tetrahedron. This plane is the boundary between potash-feldspar-bearing and potash-feldspar-free assemblages, and so the third point necessary to define this *zero microcline plane* is the point of entry of a potash-rich phase in the alkali feldspar series (along the edge N-K). From the diagram given by Laves (1952, fig. 12) it seems probable that under the hydrothermal conditions inferred for this injection episode the solvus is at about $Ab_{95}Or_5$ that is to say, in progressive potash enrichment of sodic plagioclase in a rock, potash-rich microcline will appear as a separate phase after the sodic feldspar has accommodated about 5% Or in its structure (Text-fig. 5a).

Using this diagram, the seven analyses plot as in text-fig. 5b. Although (II) does not actually contain microcline it is close to the zero microcline plane and lacks feldspar, all the alkali metals being in the white mica. The remaining rocks above the plane contain microcline, whereas I and V do not. It is worth noting that the starting materials (I) and (V) are well within the ground mapped as Lewisian by Cunningham Craig (1914) ; two other (II and III) are close to his unconformity, but in fact just within the Lewisian, whilst the remaining, more injected rocks are in his Moine area. Generally speaking Cunningham Craig's line of unconformity corresponds to the outcrop of the zero microcline plane in this ground.

The granite gneiss (VII) has not yet been definitely distinguished as pelitic or psammitic in descent. In the field the long, narrow isoclines of the two beds pass into wide, uniform granite gneiss areas, demonstrating a convergence, as already mentioned. There is no apparent way to distinguish pelitic from psammitic parentage in macroscopic or microscopic examination of these granite gneisses. From the chemical viewpoint, also, it is difficult. Many of the elements converge evenly upon rock VII. Titanium is more or less constant in the psammitic trend through to the granite gneiss, whilst it is variable in the pelitic trend. There are not enough figures to put beyond doubt this suggestion of the psammitic parentage of rock VII. For the present it seems preferable to leave the matter open. Apparently a pelitic *or* a psammitic host rock could be altered to a rock in all respects close to rock VII. Further work may produce a reliable pelitic or psammitic " fingerprint ".

The alkali injection causes a marked diminution in many trace elements, particularly from the kyanite-schist (which is rich in the rarer elements, including high vanadium, chromium, and the rare earths yttrium and lanthanum, and has relatively high titanium and nickel) to the granite gneiss. This alkali injection appears, therefore, to " rinse out " most of the trace elements from the parent rock.

By contrast, rubidium and barium rise with the increase in potash feldspar. Strontium behaves anomalously in that it does not follow calcium closely, but decreases little if at all, whereas calcium shows a considerable overall decrease. Rock III kinks many of the curves for the pelitic trend. Although it is demonstrably pelitic the former presence of kyanite cannot be proved by evidence of pseudomorphs. Perhaps although a member of the pelitic bed its composition diverged somewhat from that of the kyanite-schists proper. Many more analyses would be necessary in order to evaluate the trends thoroughly.

STRUCTURE

Cunningham Craig (1914) separated his " Lewisian " from his Moine rocks primarily on lithological grounds and secondarily on two structural grounds, namely discordance of strike and structural unconformity.

The unconformity, as already remarked, is not very clearly defined in his description, which contains caveats about the similarity in composition and even crystallization of the rocks on each side of his line, obliteration by subsequent metamorphism and so on, and rests finally upon the non-structural criterion of presence or absence of hornblendic lenticles.

Detailed search during four field seasons in the present study and mapping on a scale of 25 inches to 1 mile have failed to disclose any structural break along Cunningham Craig's line of unconformity. The tight isoclinal interfolding of a massif of gneissic Lewisian with an unconformable cover of feldspathic Moine sandstones in Caledonian times is hard to picture, particularly as the fold trend of the " dead " massif is supposed to have influenced for some distance the strike of the Moine sandstones undergoing folding and metamorphism. As has now been shown, identical hornblendic lenticles are well represented on both sides of the

" unconformity ", aiding the correlation of their identical enclosing psammitic gneisses on both sides of the " unconformity ", and identical kyanite-schists (neglecting subsequent injection) occur on each side of the line. The secondary, structural, criteria fall as soon as they lose the buttress of the more important lithological criteria for separating Moine from Lewisian along Cunningham Craig's unconformity.

The discordance between N.E.–S.W. and N.W.–S.E. strikes when no longer fenced apart by an unconformity shows every gradation between each direction and the N.W.–S.E. zone appears no more than a local swirl, of a type so common in the Moines, away from the usual N.E.–S.W. trend of the district.

The foliation of the sediment is often closely-banded and where contrasted lithologies meet (for example, kyanite-schist overlying limestone) it always parallels the sedimentary injection between the beds, showing that the foliation planes are normally bedding planes. No graded or current bedding is preserved in the tightly and plastically folded layers, and consequently " way-up " evidence is lacking. A structural succession, with the limestone at the base, can be made out in the " Lewisian " area as Cunningham Craig has shown. The tight isoclines are overturned towards the south-west and plunge consistently towards the south-east. Kyanite-schist, fresh or migmatitic, can be found directly overlying the limestone (1) in Allt Gartally near the serpentinite contact, (2) by the roadside higher up this valley, (3) at the western end of the limestone exposures at the Upper Gartally quarries, (4) 230 yards south-west of Lochan an Torra Bhuidhe, (5) the same distance west-north-west of Loch Maolachain. Kyanite-schist can be seen plunging beneath psammitic gneiss with hornblendic lenticles on the south-east slopes of Torr Buidhe.

Although the isoclinal folds are tightly compressed the fold limbs do not appear long, owing to the frequent reappearance of the lower beds as one moves across the strike. At locality (4) above (for evidence of superposition of kyanite-schist on limestone) minor limestone isoclines on an antiform crest have been pinched and sharpened into diapiric dyke-like protrusions of marble.

The isoclinal folding and the metamorphism of the sediments seem to belong, broadly, to a single episode. The many lineations measured all plunge at the same angle to the same point as the axes of the isoclinal folds, on which they appear to be the minor wrinkles. No divergent set of lineations was observed.

The serpentinite mass (Francis, 1956a) plays an important part in the structural pattern. Near its northern limit it includes a block of sediments with uninjected kyanite-schist surrounding an isoclinal core of calc-silicate rocks, representing the impure top of the limestone. In the sediments near to this part of the intrusion a detached sliver of serpentinite has been emplaced along a steep junction between kyanite-schist and limestone in an isocline, and along its eastern margin the serpentinite cuts across the strike of the folding in many places. Indeed the rocks of Sgòr Gaoithe and Upper Gartally seem to be a saddle of isoclinally folded sediments, lying across a broad back of serpentinite with complete structural discordance. These three observations suggest that the serpentinite was emplaced after at least a part of the folding and metamorphism. However, the serpentinite has apparently distorted the structures as well as cutting across them. On its west the serpentinite has an almost continuous line of kyanite-schist isoclines smeared along its margin, and parallelism of fold strikes with that margin persists for a considerable distance westwards. It suggests that the serpentinite is an inclined sill that dips towards the east, and which, in its rise, plastically deformed the " foot rock " which was bearing its weight (at the western margin) and broke through, in somewhat more brittle fashion, the "hanging rock " (at the east) which was not bearing its weight. But the picture is still further complicated by evidence of a northward drive as well as an uprise by the serpentinite mass. A band of kyanite-schist is mantled round the smooth, blunt nose of serpentinite at the north end of the mass. This band of kyanite-schist, when traced eastwards reveals a core of limestone ; it is a typical isoclinal antiform fold. The serpentinite has therefore " butted " into an already-formed fold and has wrapped it round its northern end by a northward movement during its uprise. The schists for some way north of the serpentinite show tight contortions and zig-zag crumpling (Pl. 11, fig. 1). Plunges of fold axes and linealions up to 60° have been measured, and a large hornblendic lenticle, or small silt 230 yards west-north-west of the most northerly limestone quarry has been rolled up into a perfect sphere 3 ft. in diameter. These structures call to mind the disturbed water upstream of a sunken boulder in a river.

The serpentinite, then, seems to have arrived after some of the folding, but at a time when the sediments were still plastic enough to permit it to deform them still further. The area in which the north-west to south-east, " Lewisianoid " strike of the folds is most pronounced is east of (and presumably immediately overlying) the eastwardly dipping(?) serpentinite sill. Perhaps the serpentinite, by reason of its forceful uprise, was responsible for the whole swirl of fold trends in this part of Glen Urquhart. In any event all these structures were formed before the metasomatic episode began. The serpentinite was then already in place as it has skarns developed both within and without the line of contact (Francis 1956a, 1958), and zoned hydrothermal bodies within it (Francis, 1955), which have been correlated with the alkali injection episode. It is also possible that the serpentinite, dipping below the uninjected sediments of the " Lewisian " ground, explains the lack of injection to be found there, the only largely unmigmatized ground in the schists of the Glen. The underlying serpentinite would, in this interpretation, have formed a chemical and physical barrier to uprising metasomatic fluids.

The area is also affected by the Allt Tarbh Fault, which has cut through the Moine and Old Red Sandstone north-west of Drumnadrochit (Pl. IV). It runs north-north-east to south-south-west, parallel to the Great Glen Fault and is aligned with the Allt Mòr Fault at the north-north-east (Cunningham Craig, 1914, p. 70). It probably continues south-south-east into Balmacaan Forest on the west side of Meallfuarvonie. No horizontal slickensides have been found in the Allt Tarbh shatter zone, but they are present in the Allt Mòr shatter zone, and there seems no doubt that this line is one of the sinistral wrench faults of the Highlands. Sheared rocks and gouge belonging to the fault and to a subsidiary fault parallel to and east of it can be found in the deep gorge of the Allt Tarbh at and below Mid

Balchraggan farm. Further up the hillside 250 yards north-east of West Balchraggan the fault is closely defined. On the east is Old Red Sandstone conglomerate, scarcely sheared, but with much cracking round the pebbles of siliceous and granitized gneiss which it contains. On the west of the fault the rock is composed of Moine migmatites and granite gneisses, intensely shattered and jointed, practically to the condition of a pencil slate. The west-south-west to east-north-east strike of the Moine rocks here makes an angle of about 32° to the fault in a sense which suggests sinistral tear faulting. However, the strike over the whole of Craig Achmony is rotated up to 100° from the north-west to south-east strike at Milton towards this west-south-west to east-north-east strike at the fault (see map, Pl. 14). This seems a rather large amount of cold rock to be affected in this way. Clifford (1957, p. 7) has suggested that the large Strathconon Fault may have similarly dragged round a large structure (Sgùrr an Airgid syncline) in Kintail, but doubt was cast on this suggestion in the discussion of the paper.

CONCLUSIONS

(*a*) *Age of the rocks in Glen Urquhart*

The recognition of an Inlier of Lewisian within the Moine gneisses in Glen Urquhart by the Geological Surveyors of one-inch sheet 83 (E. H. Cunningham Craig, 1914) was primarily based on lithological differences between a limestone-pelite-psammite series intruded by serpentinite on the one hand and a large uniform group of felds-pathic gneisses on the other. Secondarily, structural evidence of divergent strikes and of unconformity was invoked.

It is contended in this study that, on the contrary, the pelitic horizon (kyanite-schist) and the psammitic horizon (plagioclase-almandine psammitic gneiss, often with hornblendic lenticles) may be found on both sides of the postulated unconformity. The limestone, in the lowest structural position, simply does not reach high enough to reappear outside the unconformity, but may be at the same or similar horizon as the three Moine limestones which outcrop 7½ miles to the north-east (see map, text-fig. 1). The apparent difference between the rocks on either side of the postulated unconformity can be explained by the presence, on the " Moine side " of that line, of extensive alkali metasomatism which has changed and feldspathized the two sedimentary types, eventually causing a chemical and mineralogical convergence upon a migmatitic granite gneiss. The typical appearance of the uninjected rocks is quickly and thoroughly altered, and it is at this early stage in the metasomatism (where potash feldspar is making its first appearance in the rocks) that the line of unconformity has been drawn on the map (sheet 83). The chemical stages in the alterations have been reconnoitred with seven major and trace element analyses. Apparently this sort of metasomatism acting on trace-element-rich hosts like the kyanite-schist has the effect of "rinsing out " many of the trace-elements before the final stage of granite gneiss is achieved.

When the lithological differences between the two rock groups are no longer accepted the structural differences fall. The line of unconformity, as a structural break, has not been discovered in a long and careful search with field mapping on the scale of 25 inches to the mile. The divergence in strike appears simply as a swing or swirl in trend, as is familiar in all Moine areas. The intrusion of the serpentinite at a late stage in the folding and metamorphism (but before the metasomatism) may have played a part in modifying, locally, the strike of the folding. The area is traversed by one of the large sinistral tear faults of the Highlands.

(*b*) *Regional implications*

Glen Urquhart lies in the continuation of the so-called " flat belt " of the Upper Psammitic Group of the Moine Series. This stratigraphical-structural element, recognized by Leedal (1952) and Harry (1954) apparently continues to the Beauly Firth, and is probably bounded to the west by the line of the Strath Glass tear fault. From at least Glen Moriston to the Beauly Firth the belt is anything but flat ; plastic, isoclinal folding is apparently the rule ; nevertheless, this ground still seems to belong to the same belt as the rocks from Ardgour to Cluanie. In Glen Moriston, as in Glen Urquhart and further north, amphibolite sills and lenticles are common. No doubt the lenticles are strung-out and kneaded fragments from larger sills.

The ground in Glen Urquhart described in this paper was the only Lewisian Inlier postulated in the Upper Psammitic belt between the Great Glen and the mountains further west ; all the other Lewisian Inliers of the Northern Highlands lie nearer to the mountain front, and lower in the Moine sequence. The small outcrop of the Glen Liath series near Foyers on the other side of the Great Glen was tentatively equated with the Lewisian by Pochin Mould (1946), on the basis of similarity with the Glen Urquhart " inlier ", but in view of the conclusions of this paper regarding Glen Urquhart, the Glen Liath Series is probably not Lewisian in age.

In addition to limestones, this predominantly psammitic belt probably contains more pelitic rock than was previously recognized (map, text-fig. 1). Between Glen Urquhart and Strathglass there is shown on one-inch sheet 83 a considerable number of strips and shreds of pelitic rock, none large enough to represent a proper stratigraphical horizon. They appear to be the continuation of more substantial pelitic belts north of Erchless Castle, which ends abruptly at the River Glass. As the whole region is affected by the potash metasomatism here described, it seems clear that these strips are the fragments of larger pelitic formations now almost obliterated by metasomatism. A few of these strips have been visited during this work and they are indeed muscovitized pelitic schists surrounded by migmatites. Not a trace of any pre-metasomatism kyanite was found in those visited, but an examination of all the strips is desirable. Kyanite is well known to occur on Sgurr a' Phollain in Erchless Forest. There seems no reason to doubt Clifford's view (1958) that much of the Moine ground of this area is in the kyanite zone of regional metamorphism, although calc-silicate ribs by the road bridge at Cannich Hotel indicate the garnet zone (Kennedy, 1949).

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PLATE 11

Fig. 1. Intense crumpling of the bedding-planes of injected paragneiss north of the serpentinite mass, between Loch Maolachan and Loch Gorm. The fold axes plunge at 50°, parallel with the hammer handle, towards 123° T.

Fig. 2. Garnet in uninjected kyanite-schist, Sgòr Gaoithe. Dept. Min. and Pet. Cambridge, No. 76042. Note garnet in stable contact with biotite and also with the quartzo-feldspathic groundmass ; also the incipient spiralling of inclusions in the larger garnet. Kyanites appear on the right and below. The garnet contains some pleochroic haloes.
Magnification × 22 Ordinary light.

Fig. 3. Garnet in injected kyanite-schist, near the summit of the Kiltarlity road, Dept. Min. and Pet. Cambridge, No. 76175. The garnet is in process of attack and alteration to biotite ; it is surrounded by biotite with some muscovite. Biotite also penetrates its fractures. Elsewhere in the slide shimmer aggregate pseudomorphs after kyanite are found.
Magnification × 28 Ordinary light.

Fig 1

Fig. 2

Fig. 3

PLATE 12

Fig. 1. Uninjected kyanite-schist in the road-cutting 55 yards above the bridge, Kiltarlity road, Dept. Min. and Pet. Cambridge, No. 76038. Analysis I, Table V ; analysis of biotite, Table I, No. 1 ; R.I. (1·634) and pleochroism of the biotite, p. 171. Description in text.
Magnification × 28 Ordinary light.

Fig. 2. Strongly injected kyanite-schist from north of the drift flats of Allt an Loch Ghuirm ; Dept. Min. and Pet. Cambridge, No. 76156. Analysis II, Table V. Paragenesis 16, Table IV. Description in text.
Magnification × 28 Ordinary light.

Fig. 3. Fine-grained oligoclase-porphyroblast migmatite, near the top of the road cutting in the valley of the Gartally Burn. Dept. Min. and Pet. Cambridge, No. 76177. Analysis III, Table V. Paragenesis 9, Table IV. Description in text.
Magnification × 28 Crossed nicols.

Fig. 4. Fine-grained potassic migmatite, one-sixth mile south-east of Loch Maolachain. Dept. Min. and Pet. Cambridge, No. 76199. Analysis IV, Table V. Paragenesis 11, Table IV. Description in text.
Magnification × 28 Crossed nicols.

Fig. 1

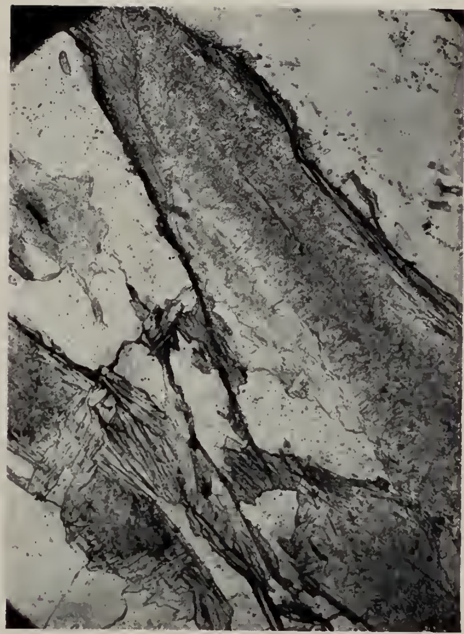


Fig. 2

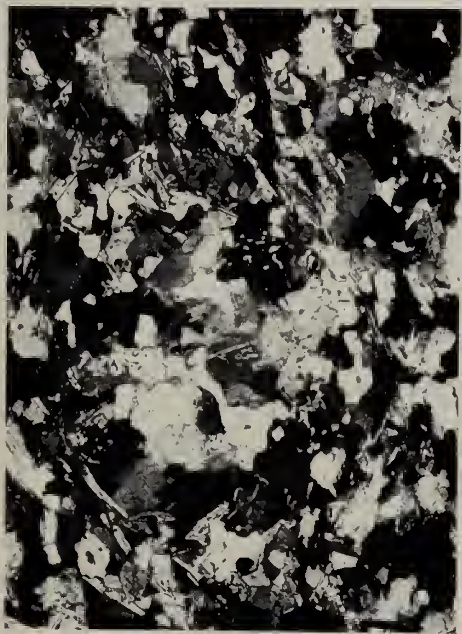


Fig. 3

Fig. 4

PLATE 13

Fig. 1. Garnetiferous gneiss, halfway between Cnoc na Moine and Loch nam Faoileag. Dept. Min. and Pet. Cambridge, No. 76055. Analysis V, Table V. Paragenesis 3, Table IV. Description in text. Original material of the psammitic series.
Magnification × 22 Ordinary light.

Fig. 2. Sodi-potassic migmatite, from lower crest of Craig Achmony overlooking Kilmichael. Dept. Min. and Pet. Cambridge, No. 76202. Analysis VI, Table V. Paragenesis 18, Table IV. Description in text. To show the appearance of microcline, revealed by staining, on one side of the field only.
Magnification × 22 Ordinary light.

Fig. 3. The same as B, with lower magnification to show a wider field.
Magnification × 9 Ordinary light.

Fig. 4. Migmatitic granite-gneiss, from just below (east of) the summit of Craig Achmony. Dept. Min. and Pet. Cambridge, No. 76203. Analysis VII, Table V. The end product of the potassic metasomatism, both of the pelitic and psammitic series. Description in text.
Magnification × 22 Ordinary light.

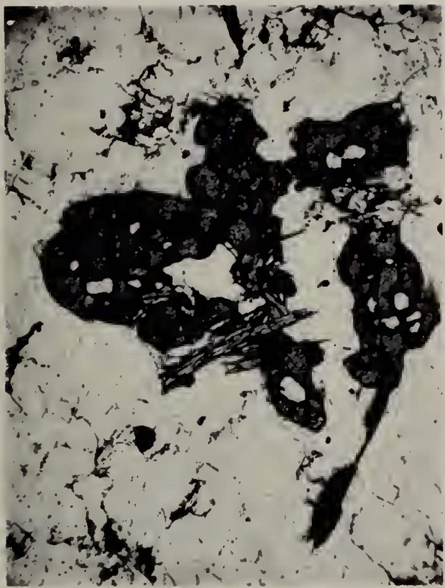


Fig. 1

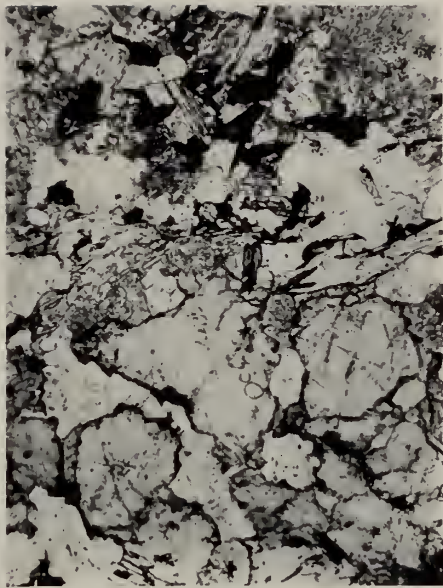


Fig. 2

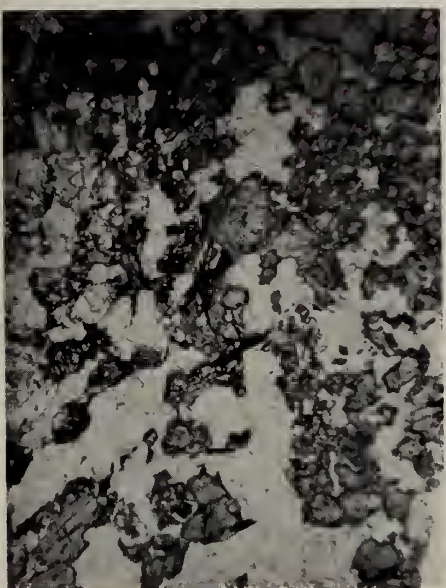


Fig. 3

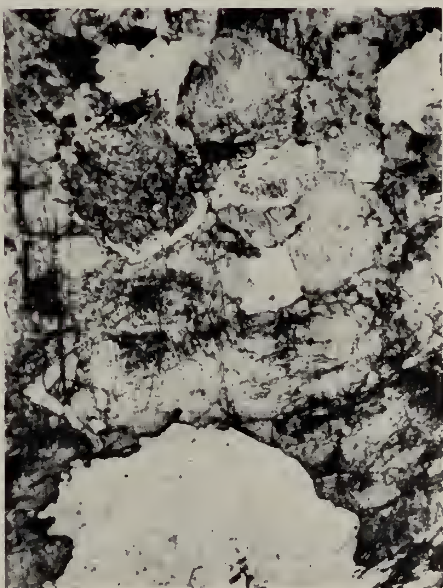
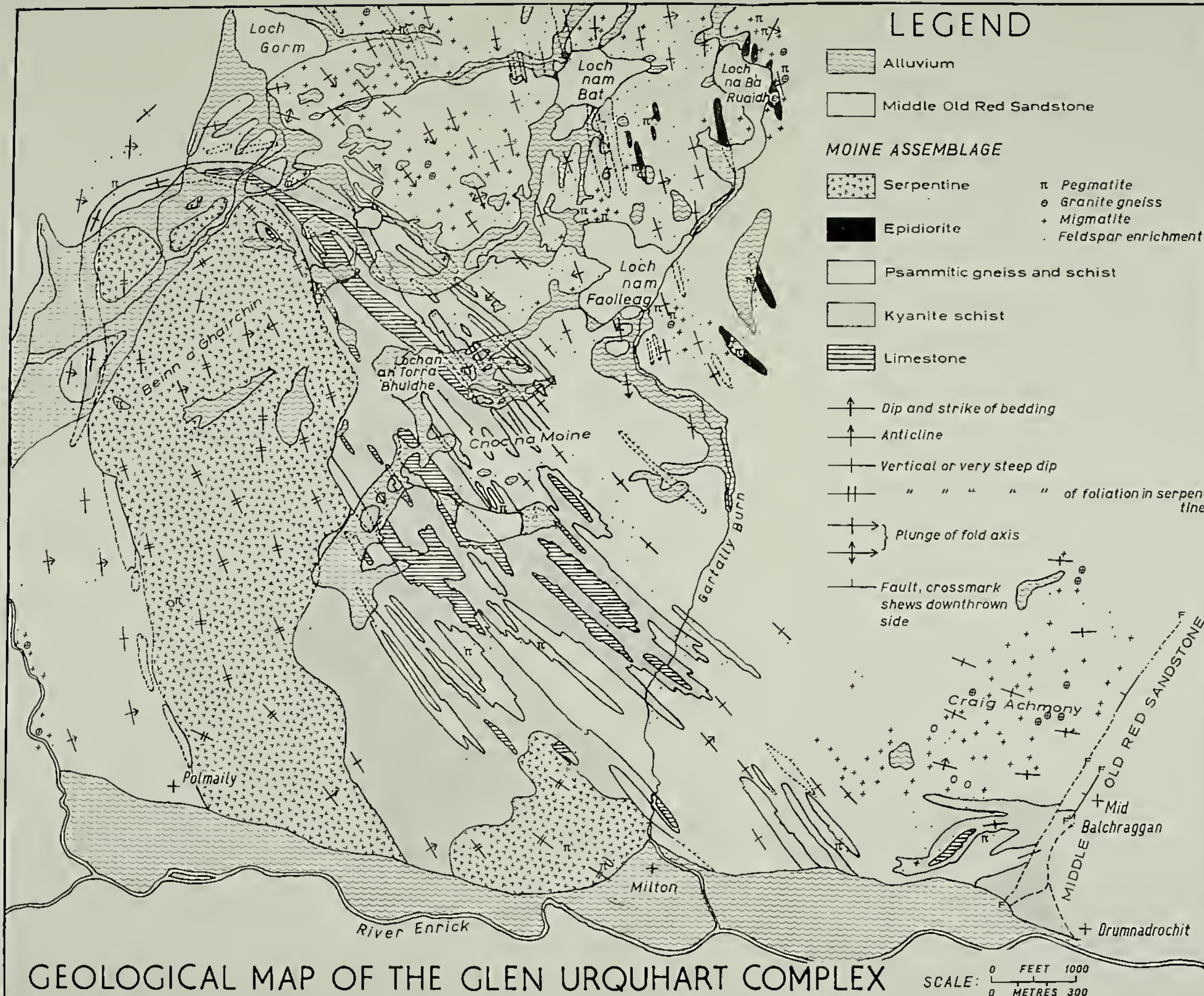


Fig. 4

PLATE 14

Geological map of the Glen Urquhart complex, to show distribution of the evidence of potash metasomatism. Reduced and simplified from the author's map on the scale of approximately six inches to the mile.



GEOLOGICAL MAP OF THE GLEN URQUHART COMPLEX